Advanced System for the Retrieval of Spectral Beam Attenuation Coefficient (*c*)

ZhongPing Lee
Naval Research Laboratory, Code 7333
Stennis Space Center, MS 39529
phone: (228) 688-4873   fax: (228) 688-4149   email: zplee@nrlssc.navy.mil

LONG-TERM GOALS

The long-term goal of this project is to have an advanced algorithm for beam attenuation coefficient (*c*) from ocean color remote sensing, an algorithm that can be implemented to process satellite imagery for Navy applications.

OBJECTIVES

The primary objectives of this research are: 1) to identify the most significant proxy (or proxies) that can be used to represent the change of backscattering (b_b) to scattering (*b*) ratio (i.e., b_b/b); and 2) to develop an algorithm that can be used with data from satellite ocean color remote sensing to provide needed global coverages of beam attenuation coefficient.

APPROACH

Beam attenuation coefficient (*c*) is an important parameter regarding water quality. Traditionally, estimation of *c* from measurements of ocean color was taken empirically: one was to relate *c* with remote-sensing reflectance in the longer wavelengths (Gould and Arnone, 1997a); another was to convert remotely derived backscattering coefficient (b_b) to total scattering coefficient (*b*) with a constant b_b/b ratio (Gould and Arnone, 1997b), and then add absorption coefficient (*a*) (*c* is the sum of *a* and *b*). Results from both approaches, however, contain large uncertainties due to that the assumptions (explicit or implicit) of constant b_b/b ratio used in those algorithms are only valid for limited waters. Therefore it is difficult to extend these approaches to waters of the global oceans where the Navy is interested.

Fundamentally, sensors mounted in a "remote" platform looking downward (toward greater depths) measure signals going upward, which are primarily generated by backward scattering. Numerical and theoretical studies have found that the intensity of this upward signal is quite insensitive to the forward scattering (Gordon, 1993), suggesting little forward information could be analytically derived from remotely collected data. On the other hand, because *b* is the major contributor to *c* and forward *b* makes a significant (98% or more) portion of *b* value, it is then intrinsically difficult (if not impossible) to *analytically* derive *c* from remotely sensed ocean color. Realizing this fact, remote estimation of *c* will always be empirical or semi-empirical in nature.

Our approach is to study the link between particle's backscattering to scattering ratio (b_{bp}/b_p) and the inherent optical properties (in particular, absorption (*a*) and backscattering (b_b) coefficients plus the

1. REPORT DATE **30 SEP 2006**	2. REPORT TYPE	3. DATES COVERED **00-00-2006 to 00-00-2006**
4. TITLE AND SUBTITLE **Advanced System for the Retrieval of Spectral Beam Attenuation Coefficient (c)**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Research Laboratory,Ocean Optics Section Code 7333,Stennis Space Center,MS,39529-5004**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**5**	

spectral slope of particle scattering (Y)). It is well known that b_b (and then b_{bp}) and a can be adequately retrieved from remotely sensed ocean-color data such as remote-sensing reflectance (R_{rs}), and that algorithms (the quasi-analytical algorithm (QAA, Lee et al., 2002) in particular) for the derivation of those properties have been developed. The missing piece of information is how to accurately convert b_{bp} to b_p, where b_{bp}/b_p ratio can vary from as low as 0.5% for phytoplankton to as high as 8% for suspended sediments. Studies have found that b_{bp}/a is a good index about water mass character (Loisel et al., 2002) and Y a good index of the distribution of particle sizes (Boss et al., 2001). We thus hypothesized that change of b_{bp}/b_p could be modeled using values of inherent optical properties that could be derived from remote sensing.

WORK COMPLETED

In an earlier phase of this project, we compiled a large (N = 136) data set with concurrent measurements of beam attenuation coefficient at 555 nm ($c(555)$) and spectral remote-sensing reflectance (R_{rs}). These measurements covered wide range of waters around the coasts of the United Sates, and were taken from seven cruises in the period of 1996 – 2004. We tested the performance of the earlier empirical algorithms for c (Gould and Arnone, 1997a, 1997b) with this data set, and R^2 (correlation of determination) value of 0.65 and averaged percentage error over 100% were obtained (Lee et al. 2006). These results indicate the limitations of such kinds of empirical algorithms to wide range of waters and the desire to have a better algorithm (or algorithms). To improve the estimation of beam c from remote sensing, we identified the prominent proxies to indicate a change of b_{bp}/b_p ratio, and completed the development of algorithm to estimate b_{bp}/b_p from values of inherent optical properties (Lee et al. 2006). With absorption and backscattering coefficients derived from R_{rs} using the QAA algorithm, and the relationship between b_{bp}/b_p and IOP, beam c was calculated semi-empirically from R_{rs} (Lee et al. 2006). This new approach leads to a factor of three reduction in the error of remotely derived $c(555)$ for the same data set (Lee et al. 2006), with R^2 of 0.84 and average percentage error of ~33% achieved.

Lately, we have completed new measurements made in the Gulf of Mexico (May 2005) and the Mississippi Sound (December 2005). Values of beam attenuation coefficient at four wavelengths (440, 490, 530, and 555 nm) were derived from R_{rs} with the new algorithm and validated with measurements from water samples (measured by AC-9).

RESULTS

Figure 1 presents results of an independent validation of the newly developed hybrid-algorithm for beam attenuation coefficient (c). For c values at 440, 490, 530, and 555 nm, all in a range of ~0.2 – 5.0 m^{-1}, the average percentage errors are 18.3%, 16.5%, 16.2%, and 16.7%, respectively. These results demonstrated that the applicability and robustness of this new algorithm, which effectively taking account the change of water mass, to estimate beam c from remote sensing of ocean color for oceanic and coastal waters. We did experience larger errors (underestimate by ~50-60%) in retrieving c of river or river plume waters (with c value greater than 10 m^{-1}), however. This could be resulted from two fronts. First the algorithm to derive absorption and backscattering coefficients was not designed for such kind of extreme waters. And secondly the empirical relationship to get b_{bp}/b_p may not be appropriate for such waters. Preliminary studies seem indicate that most of the errors came from the application of QAA to such kind of waters.

With the completion of these tests and evaluations, we have achieved the goals for this study: algorithm development. We are planning to take more measurements from different environments and further the test and evaluation. We are also preparing to incorporate this algorithm to the NRL APS system to derive beam attenuation coefficient for oceanic and coastal waters from satellite measurements.

IMPACT/APPLICATIONS

Accurate determination of beam attenuation coefficient is of important applications in Navy operations, such as visibility, laser transmission and underwater imaging, etc. Also, the derived optical properties can help analyze particle characteristics (Twardowski et al., 2001). With extended validation and fine tuning, the approach/algorithm developed from this study can be used to provide worldwide coverage where Navy operations are desired.

RELATED PROJECTS

Validation of spectral and IOP particle characteristics (Funded by Code 32 ONR).
Through the sensor derived optical properties and image enhancement (NRL Core funding).

REFERENCES

Boss, E., Twardowski, M.S. and Herring, S., 2001. Shape of the particulate beam attenuation spectrum and its inversion to obtain the shape of the particulate size distribution. Applied Optics, 40(27): 4885-4893.

Gordon, H.R., 1993. Sensitivity of radiative transfer to small-angle scattering in the ocean: Quantitative assessment. Applied Optics, 32: 7505-7511.

Gordon, H.R. and Clark, D.K., 1980. Remote sensing optical properties of a stratified ocean: an improved interpretation. Applied Optics, 19: 3428-3430.

Gould, R.W. and Arnone, R., 1997a. Estimating the beam attenuation coefficient in coastal waters from AVHRR imagery. Cont. Shelf Res., 17(11): 1375-1387.

Gould, R.W. and Arnone, R., 1997b. Remote sensing estimates of inherent optical properties in a coastal environment. Remote Sens. Environ., 61: 290-301.

Lee, Z.P., Carder, K.L. and Arnone, R., 2002. Deriving inherent optical properties from water color: A multi-band quasi-analytical algorithm for optically deep waters. Applied Optics, 41: 5755-5772.

Lee, Z.P., A. Weidemann, R. Arnone, R. Gould, W.A. Goode, Z. Fei, "Beam attenuation coefficient of coastal waters: A new remote sensing model," Ocean Science Meeting 2006.

Loisel, H., Nicolas, J.M., Deschamps, P.Y. and Frouin, R., 2002. Seasonal and inter-annual variability of the particulate matter in the global ocean. Geophys. Res. Lett., 29(24): 2196, doi:10.1029/2002GL015948.

Twardowski, M.S. et al., 2001. A model for estimating bulk refractive index from the optical backscattering ratio and the implications for understanding particle composition in case I and case II waters. J. Geophys. Res., 106(C7): 14,129-14,142.

PUBLICATIONS

IOCCG, "Remote Sensing of Inherent Optical Properties: Fundamentals, Testing of Algorithms and Applications", Lee, Z.-P. (ed), GKSS, September, 2006. [published]

Lee, Z. P., K.P. Du, R. Arnone, S.C. Liew, B. Penta, "Penetration of solar radiation in the upper ocean – A numerical model for oceanic and coastal waters," *J. Geophys. Res.*, *110*, C09019, doi:10.1029/2004JC002780, 2005. [published, refereed]

Lee, Z. P., C. Hu, "Global distribution of Case-1 waters: An analysis from SeaWiFS measurements" *Remote Sens. Env.*, 101, 270-276, 2006. [published, refereed]

Lee, Z.P., A. Weidemann, R. Arnone, R. Gould, W.A. Goode, Z. Fei, "Beam attenuation coefficient of coastal waters: A new remote sensing model," Ocean Science Meeting 2006. [published]

Lee, Z.P., A. Weidemann, J. Kindle, R. Arnone, K.L. Carder, C. Davis, "Euphotic zone depth: Its derivation and implication to ocean-color remote sensing," *J. Geophys. Res.*, accepted, 2006.

Hu, C., Z. P. Lee, F.E. Muller-Karger, K.L. Carder, and J.J. Walsh, "Ocean color reveals phase shift between marine plants and yellow substance," *IEEE Geoscience and Remote Sensing Letters*, Vol.3, 262-266, 2006. [published, refereed]

Craig, S. E., S. E. Lohrenz, Z.-P. Lee, K. L. Mahoney, G. J. Kirkpatrick, O. M. Schofield, R. G. Steward, "Use of Hyperspectral Remote Sensing Reflectance for Detection and Assessment of the Harmful Alga, *Karenia brevis*," *Appl. Opt.*, , 45(21), 5414-5425, 2006. [published, refereed]

Liu, C.-C., R.L. Miller, K.L. Carder, Z.P. Lee, E.J. D'Sa, J.E. Ivey, I.-I. Lin, "Estimating the underwater light field from remote sensing of ocean color". *J. Oceanogr.*, 2006. **62**: p. 235-248. [published, refereed]

Wu, J., H. Hong, S.L. Shang, M. Dai, Z.P. Lee, "Variation of phytoplankton absorption coefficients in the northern South China Sea during spring and autumn," *J. Marine Research*, submitted, 2006.
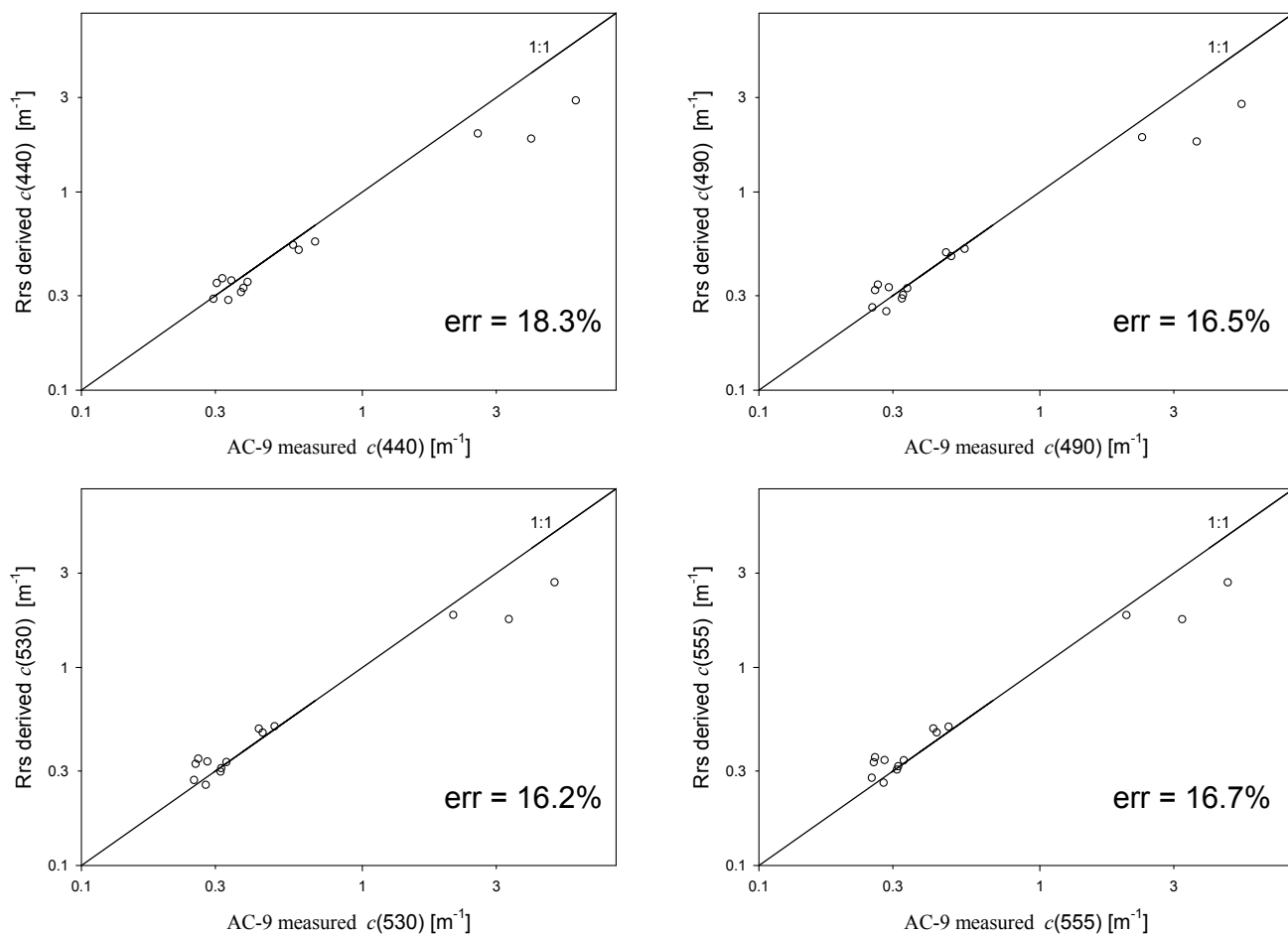
Figure 1. Preliminary evaluation of the newly developed hybrid-algorithm for beam attenuation coefficient. Measurements were made in the Gulf of Mexico and the Mississippi Sound in 2005.